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CONTROL OF WIREWORMS IN CALIFORNIA WITH THE SOIL FUMIGANTS CHLORINATED PROPANE-PROPYLENE AND ETHYLENE DIBROMIDE [1]

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Preliminary experiments to determine the effectiveness of the soil fumigant chlorinated propane-propylene (a mixture of 1,2-dichloropropane and 1,3-dichloropropylene) on the sugar-beet wireworm (*Limonius californicus* Mann.) in lima beans were begun at Ventura, Calif., in 1943, and large-scale field experiments in 1944. Preliminary experiments with ethylene dibromide were begun in 1944 and field experiments in 1945. The progress made during the last 5 years is summarized in this paper.

PREVIOUS WORK

Carter (2, 3) found D-D mixture (chlorinated propane-propylene) to be effective in controlling soil organisms affecting pineapple in the Hawaiian Islands. Stone (10) reported on the toxicity to wireworms of emulsifiable dichloropropane-dichloropropylene. Lange (5, 6, 7) summarized the results obtained in field tests with a mixture of dichloropropane and dichloropropylene and with ethylene dibromide on wireworms in the Salinas Valley, Calif., and recommended dosages. Tam (11) reported the effect of this mixture on nitrification in soil and on the growth of pineapples. Newhall (8) found that it was an excellent nematocide when used in large quantity, and that it had rather limited fungicidal and herbicidal properties. Schmidt (9) compared the dispersion of this mixture and chloropicrin through soils of different moisture content. Cook (4) compared the effectiveness of ethylene dibromide, dichloronitroethane, and chlorinated propane-propylene against wireworms under various temperatures and soil conditions.

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[1] The experiments reported here were conducted with the assistance of W. Balch and L. S. Hannibal, of the Shell Chemical Corp., J. F. Kagy, R. L. McPherson, and A. W. Swezey of the Dow Chemical Co., and the following bean growers: H. Bruns, R. Borchard, J. Laubacher, G. Chaffee, and H. Grether. The following field assistants helped to obtain the data on wireworm populations: S. Stuart, G. Claypool, J. Pinkerton, R. Hudson, and C. Craven.

MATERIALS USED

The chlorinated propane-propylene contained approximately 33 percent of 1,2-dichloropropane, 63 percent of 1,3-dichloropropylene, and about 4 percent of heavy trichlorides of propane. It was used undiluted. Ethylene dibromide was used in 5, 10, and 20 percent (by volume) solutions in a petroleum naphtha thinner having a boiling range of 173° to 246° F.

PROCEDURE

The experiments were conducted in fields usually kept fallow during the winter months and until the time of planting lima beans in May. Many of these fields were so heavily infested with wireworms that portions had to be replanted each year; in many instances these second plantings were also damaged extensively. Since the tests were to be carried on for several years, large plots ranging from 1/4 to 1/2 acre in size were used. Since these plots were never less than 40 feet wide, larval migration was not a problem.

The treatments were usually made in March, April, or May, in fields that had been thoroughly worked and were in shape as for the planting of beans. Crop remnants caused no difficulty, as the bean straw from the previous crop was well rotted at the time of treatment. Nor was cloddy soil a problem, as growers cooperated well in getting their fields in excellent condition for treatment. The soil in the experimental plots was classified as Yolo sandy and silt loams. Its moisture content was variable, depending upon the winter rainfall or whether or not the fields had been irrigated.

Various methods were employed in evaluating the results. In sampling to determine wireworm populations, random soil samples one quarter square foot in size were taken with a soil auger. From 12 to 20 soil samples 16 inches deep were taken at random in each plot before and 10 to 14 days after the soil was treated. The wireworms were recovered by sifting each sample in the soil sifter according to the technique described by Campbell and Stone (1). After the beans had been planted, usually 5 to 7 days later, 8 soil samples 3 feet long, 4 inches wide, and 4 to 6 inches deep were taken at random in the bean rows of each plot, and each sample was sifted. A 0.01-acre area (4 rows 43½ feet long) was staked out in the center of each plot before the beans emerged. The plants in this area were counted at harvesttime. Yield data were obtained by picking and weighing the green lima beans or by threshing the dry lima beans from this area. In one experiment lasting 3 years the grower kindly threshed all the beans in 20 one-fourth acre plots.

Promising results had been obtained with chlorinated propane-propylene when the emulsifiable material was applied in irrigation water (Stone 10). Obviously, this method of application would be limited to areas with irrigation facilities. During periods of heavy rainfall it would not be practical to irrigate in order to apply chemicals solely for the control of soil pests. It appeared desirable, therefore, to concentrate on the injection method of applying fumigants in the soil.

Prior to 1944 only small, hand-operated injector apparatus capable of delivering a single dose was available. In 1944 an experimental model of a small garden tractor applicator with three blades proved very efficient (fig. 1). The equipment included a 6-gallon stainless-steel tank and a small belt-driven pump operated by a pulley on the power takeoff shaft on the tractor. Steel pipes and plastic tubing (i.d. 1/4 inch) were used to convey the liquid fumigants to steel tubes (bore diameter 1/4 inch) welded on the rear of the three injector blades. A pressure regulator was used to regulate the rate of flow. The injector blades were clamped at the desired spacing to the drawbar on the tractor, which could be raised or lowered depending on the depth the fumigant was to be injected into the soil. Heavy grooved steel wheels attached to supports on the rear of the tractor served to seal the openings made by the blades. By adjusting the regulator and maintaining a constant speed, it was possible to apply liquid fumigants in a continuous flow accurately at rates ranging from 10 to 60 gallons per acre.

In 1945 large experimental tractor-driven applicators with five to eight blades were used in treating the plots established in that year. Later implement manufacturers and commercial insecticide dealers designed and constructed various types of power machines for applying soil fumigants (figs. 2 and 3).

EXPERIMENTS WITH CHLORINATED PROPANE-PROPYLENE

Preliminary Tests

Beginning in 1944 preliminary tests with chlorinated propane-propylene were conducted on 1/4-acre plots in the H. Bruns field. The soil was Yolo sandy loam with a moisture content (dry weight) ranging from 14 percent at a depth of 4 inches to 13.6 percent at 16 inches. Soil temperatures reached 70° F. at 4 inches and 61° at 12 inches on March 23, the date of treatment. The material was applied with the garden tractor applicator at a depth of 5 inches, at 18-inch spacings, at the rates of 20, 26, and 35 gallons per acre. A heavy beet roller was used to pack the soil immediately after treating it. Four alternate untreated plots served as checks. There was little difference in the effectiveness of the three dosages. The treated and the untreated plots averaged 1.9 and 1.8 wireworms per square foot before treatment and 0.1 and 2.2 wireworms per square foot, respectively, after treatment. The wireworm population of the bean rows was reduced accordingly from 1.8 per foot in the untreated plots to 0.5 in the treated plots. There was a good stand of lima beans in all the treated plots, whereas in the untreated plots the wireworms had thinned the stand considerably.

On April 23 additional tests were conducted on the G. Chaffee farm in soil of the same texture. The moisture content averaged 8.5 percent at the 4-inch depth and 18.4 percent at the 16-inch depth. Soil temperatures averaged 65°, 63°, and 65° F. at the 4-, 8-, and 12-inch depths, respectively. One-ninth-acre plots were treated in duplicate at the rates of 17, 31, and 40 gallons per acre. The same procedure and equipment were used as in the preceding tests. Lima beans were planted in these plots on May 20. Counts made before and after treatment showed reductions in wireworm populations ranging from 38 percent in the plots treated with 17 gallons to 50 and 86 percent in the plots treated with 31 and 41 gallons per acre. The wireworm populations of the bean rows were reduced accordingly from 3.2 per foot in the check plots to 1.9, 0.3, and 0.2 per foot in the treated plots. From 15 to 21 pounds of dry beans per 0.01 acre were harvested in the treated plots as compared with only 4 pounds in the untreated plots.

Tests were also conducted on the J. Laubacher farm, in Yolo sandy loam where wireworms had been a serious problem for years. The material was applied to 1/8-acre plots on April 11, 1944, at rates ranging from 10 to 58 gallons per acre. Each treatment and check was replicated three times in a randomized-block layout. As in the preceding tests, the chemical was applied 5 inches deep, at 18-inch spacings. To seal the surface the plots were clod-mashed after being treated. The soil was moist even near the surface, the moisture content ranging from 11.9 percent at the 4-inch depth to 17.3 percent at the 16-inch depth. Soil temperatures reached maxima of 73°, 70°, and 68°, respectively, at the 4-, 8-, and 12-inch depths. Fordhook beans were planted on May 23, after the area had been spring-toothed to aerate the soil. The same crop was planted in 1945 and 1946. The wireworm populations, stand counts, and yields in each of these years are shown in table 1.

The results obtained by sifting soil samples show that dosages of 20 gallons and higher caused a significant reduction in wireworm populations for a 2-year period. Owing to this reduction excellent yields of green beans were obtained the first year in the plots treated with these dosages. The highest dosage gave an exceptionally good initial kill, and the wireworm populations in the bean rows remained low. In both 1945 and 1946 excellent yields of beans were obtained in the untreated as well as in the treated plots.

Field Tests

The results of the preliminary tests with chlorinated propane-propylene on wireworms showed considerable promise. It appeared, however, that the initial kill could be improved by applying the material at closer spacings. Beginning in 1945 portions of two lima bean fields were used for further tests along this line. Both fields contained very fine sandy loam soil. In the Bruns field 1/3-acre plots were treated at rates of 22, 40, and 55 gallons per acre. Each treatment and check was

Table 1.--Results of preliminary tests with chlorinated propane-propylene against wireworms in a field of green Fordhook beans. J. Laubacher field. Plots treated in 1944 only.

Gallons per acre	Wireworms per square foot			Wireworms per foot of bean row			Plants per foot of bean row			Yield of beans per 0.01 acre		
	1944		1945									
	Before treatment	After treatment		1944	1945	1946	1944	1945	1946	1944	1945	1946
	Number	Number	Number	Number	Number	Number	Number	Number	Number	Pounds	Pounds	Pounds
0	1.5	1.2	1.7	1.6	1.5	0.6	1.2	1.2	1.3	91	97	126
10	1.0	1.2	1.0	1.4	.8	.4	1.1	1.3	1.3	93	101	136
20	1.8	.5	.9	.9	.5	.3	1.2	1.4	1.3	111	110	150
32	2.6	.5	.7	.6	.2	.6	1.3	1.4	1.4	111	113	139
40	2.7	.4	.7	.4	.4	.5	1.2	1.2	1.3	120	102	127
58	1.5	.2	.1	.1	.1	.3	1.5	1.4	1.3	123	112	134
Difference required for significance (odds 19:1):												
	1/	.5	.9	.8	1/	1/	1/	1/	1/	1/	1/	1/

1/ Not significant according to F test.

replicated six times in a randomized-block layout. In the Laubacher field the fumigant was applied on 1/4-acre plots at 22, 41, and 61 gallons per acre. There were only four replications of each treatment and check arranged in randomized blocks. All dosages were applied 7 inches deep, at 15-inch spacings, in soil that had been disked 8 inches deep and clod-mashed. The moisture content of the soil in the two fields at the time of treatment (April 10-13) averaged 12 percent (by weight) at the 4-inch depth and 13-17 percent at the 16-inch depth. Soil temperatures ranged from 60° to 65° F. at the 6-inch depth and from 59° to 63° at the 12-inch depth.

In the Bruns field lima beans were planted in 1945, 1946, and 1947 on May 8, 15 and 1, respectively, and harvested on September 6 and 13, and August 26. In the Laubacher field lima beans were planted in 1945 on May 14 and the dry beans were harvested on September 15. Fordhook beans for processing were planted in 1946 and 1947 on May 20 and 7 and were harvested on August 26 and 25. To avoid plant injury from the higher dosages, the soil in both fields was thoroughly aerated by harrowing before the beans were planted in 1945. The results obtained in the two fields are shown in table 2.

In 1945 all dosages caused significant reductions in wireworm populations and increases in the yields of dry beans in both fields, and especially in the Bruns field. A heavy infestation of Lygus bugs in the Laubacher field may have accounted for the poor and erratic yields obtained in these plots. Initial wireworm populations in this field were high. The treated plots in both fields had an exceptionally good stand of beans, whereas in the untreated plots only about one-half a stand remained and many of these plants were badly injured.

In 1946 the untreated plots had very low wireworm populations and produced about the same yields as did the treated plots. The only explanation for this unusual occurrence is that weather conditions during the year 1945 were more favorable for wireworm activity than the year 1946, as was indicated by the widespread damage to beans, and most of the wireworms transformed to adults in that year. The larvae from eggs deposited by these adults in 1946 would not cause damage until 1947. In 1947 the wireworm populations sharply increased in all treated plots except those in the Laubacher field receiving the 61-gallon dosage. No doubt the heavily infested plots had become repopulated either by ovipositing adults from the previous year's brood or by larvae from the lower depths of the soil that had escaped treatment in 1945. In the Laubacher field significantly higher yields of green Fordhook beans were obtained in all treated plots in 1947 than in the untreated plots, whereas in the Bruns field no differences in yields were noted.

Table 2.—Control of wireworms over a 3-year period by fumigation of the soil in two fields with chlorinated propane-propylene in 1945.

Gallons per acre	Wireworms per square foot 1945 Before treatment	Wireworms per square foot 1945 After treatment	Wireworms per square foot 1946	Wireworms per foot of bean row 1945	Wireworms per foot of bean row 1946	Wireworms per foot of bean row 1947	Plants per foot of bean row 1945	Plants per foot of bean row 1946	Plants per foot of bean row 1947	Yield of beans per 0.01 acre 1945	Yield of beans per 0.01 acre 1946	Yield of beans per 0.01 acre 1947
	Number	Number	Number	Number	Number	Number	Number	Number	Number	Pounds	Pounds	Pounds
Bruns Field												
0	1.2	1.7	0.5	2.6	0.4	1	0.6	1.1	1.1	8	21	21
22	1.9	.3	.3	.5	.1	.9	1.1	1.2	1	20	20	20
40	1.7	.1	0	.2	.1	.8	1.2	1.3	1	19	23	20
55	1.8	0	0	.1	0	.8	1.2	1.3	1.1	19	22	21
Difference required for significance (odds 19:1):	1/	1	.2	.7	.1	1/	.3	1/	1/	5	2	1/
Laubacher Field												
0	3.8	2.8	1.9	5.4	0.9	1.4	1	1.3	0.8	6	105	44
22	3.1	.2	.5	.7	.3	.6	1.9	1.7	1.3	9	125	75
41	2.8	.2	.1	.4	.2	.9	1.9	1.7	1.1	11	123	88
61	3.9	.2	.3	.3	.1	.2	1.8	1.7	1.2	11	126	100
Difference required for significance (odds 19:1):	1/	.9	1.3	1.6	.5	1/	.5	.3	1/	1/	1/	10

1/ Not significant according to *F* test.

EXPERIMENTS WITH MISCELLANEOUS SOIL FUMIGANTS

In 1944 a number of fumigants were applied in the soil to determine their effectiveness on wireworms. The garden tractor applicator was used to apply the materials 5 inches deep, at 18-inch spacings, in single plots 1/8 acre in size. The soil was Yolo fine sandy loam with a moisture content ranging from 12 percent at the 4-inch depth to 17 percent at the 16-inch depth. The following materials were tested:

Dichloroisopropyl ether
Dichloroisopropyl ether plus 10 percent of methyl iodide
Dichloroisopropyl ether plus 10 percent of methyl bromide
Ethylene dichloride plus 10 percent of methyl iodide
Ethylene dichloride plus 10 percent of methyl bromide
Ethylene dichloride-chloropicrin (80:20) plus 10 percent of methyl iodide
Chlorinated propane-propylene
Ethylene dichloride plus 10 percent of ethylene dibromide
Tetrachloroethane plus 10 percent of methyl bromide
Tetrachloroethane plus 20 percent of chloropicrin

The first five materials were applied on April 18 and the remainder on May 15. On these days soil temperatures reached 78° F. at 4 inches and 67° at 12 inches. After the treatment the soil surface was clod-mashed and, before Fordhook beans were planted on May 30, was spring-toothed and again clod-mashed.

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Dichloroisopropyl ether proved to be of no value as a soil fumigant for wireworms. When this material was combined with methyl bromide or methyl iodide, plant growth was retarded and many plants appeared deformed. The mixture of ethylene dichloride and methyl bromide proved to be toxic to wireworms and was not injurious to bean plants. When ethylene dichloride was combined with methyl iodide, however, some of the plants appeared stunted.

The mixtures containing ethylene dibromide appeared to be the most promising. The ethylene dichloride-chloropicrin-methyl iodide and the tetrachloroethane-methyl bromide mixtures definitely retarded the growth of Fordhook beans, and there were no signs of recovery. The stems on the emerging bean seedlings in the plot treated with a mixture of tetrachloroethane and chloropicrin had a dark greenish tinge, but this color soon disappeared.

EXPERIMENTS WITH ETHYLENE DIBROMIDE

Experiment in Chaffee Field

Because of the favorable results obtained with ethylene dibromide in 1944, an experiment was begun in the Chaffee field in 1945 to compare the effectiveness of this material at concentrations of 5, 10, and 20 percent

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(by volume) in naphtha thinner. The treatments were applied with a large experimental tractor-driven applicator at a rate approximating 40 gallons per acre. The plots were 0.4 acre in size and each treatment and check was replicated four times in a randomized block layout. The fumigant was applied 7 inches deep at 12-inch spacings. The soil was Yolo sandy loam with a moisture content of 10.1 percent (by weight) at the 4-inch depth, 16.8 percent at the 8-inch depth, and 17.8 percent at the 16-inch depth. Before the soil was treated, it was disked 8 inches deep and clod-mashed. Maximum soil temperatures on the day of treating, April 17, were 68° F. at 6 inches and 64° at 12 inches. Lima beans were planted on May 15.

No wireworms were recovered and no damage to the germinating beans was noted in any of the treated plots. In contrast, many of the beans in the check plots were destroyed by the heavy populations of worms, and the stand as well as the yield of beans in these plots was reduced accordingly. The yields of dry beans in the treated plots were not so high as was anticipated, probably because the beans had been planted too thick and had not been irrigated during the summer months. Sugar-beets were planted in these plots on February 27, 1946, and to obtain additional data on wireworm populations four soil samples were taken in the beet rows 4 weeks after planting and sifted. In the treated plots there was a good stand and no wireworms were recovered in the soil samples. In comparison, the untreated plots had a thin stand due to the destructiveness of the wireworms present.

Experiment in Laubacher Field

A field on the Laubacher farm that had been planted to lima beans on May 5, 1945, was so badly damaged by wireworms after 3 weeks that the owner decided to disk and replant. A 5-acre portion of this field was divided into twelve 0.4-acre plots. Concentrations of 2.5, 5, and 10 percent (by volume) of ethylene dibromide in naphtha thinner were applied on May 28. The same procedure and equipment were used as in the preceding tests. After treatment, the soil was clod-mashed and then planted to Fordhook beans on June 2. The soil in this field was Yolo very fine sandy loam and had moisture contents of 9.5, 14.4, 15.1, and 16 percent (by weight) at depths of 4, 8, 12, and 16 inches, respectively. Soil temperatures averaged 65° F. at the 6-inch depth and 62° at the 12-inch depth. The results of these tests are summarized in table 3.

On the third or fourth day after treatment the plots were heavily infested. All concentrations appeared equally effective, as no wireworms were recovered in any of the treated plots. The beans in the check plots, where there were more than 4 wireworms per foot of row, were badly damaged and the yields were poor.

In 1946, when green Fordhook beans were planted in these plots, there was a sharp decrease in the wireworm population of the bean rows in the check plots, and the yields of beans exceeded those obtained in the treated plots. Possibly because of favorable temperatures, soil moisture, and ample food in 1945, wireworm activity and feeding were accelerated and most of the larvae transformed to adults in that year.

Table 3.--Control of wireworms by fumigation of the soil with various concentrations of ethylene dibromide in naphtha thinner. Laubacher field. Plots treated in 1945 only.

Percent ethylene dibromide	Rate per acre	Wireworms per square foot after 3 or 4 days	Wireworms per foot of bean row		Plants per foot of bean row		Yield of beans per 0.01 acre	
			1945	1946	1945	1946	1945	1946
	Gallons	Number	Number	Number	Number	Number	Pounds	Pounds
Check	0	5.3	4.2	0.2	0.2	1.7	8	89
2.5	39	7.5	0	.1	1.6	1.7	50	78
5	25	6.5	0	.01	1.3	1.8	48	81
10	36	5.2	0	0	1.1	1.7	54	86
Difference required for significance (odds 19:1):		—	--	--	.2	[1]	20	[1]

[1] Not significant according to *F* test.

COMPARATIVE EFFECTIVENESS OF CHLORINATED PROPANE-PROPYLENE AND ETHYLENE DIBROMIDE

Field Experiments Begun in 1946

Field experiments in 1946 were set up to compare the effectiveness of chlorinated propane-propylene and ethylene dibromide as soil fumigants on wireworms. One-fourth-acre plots were laid out in a heavily infested 5-acre portion of the R. Borchard field near Oxnard. The soil was Yolo very fine sandy loam with a moisture content ranging from 6.4 percent at the 4-inch depth to 13.1 percent at the 12- to 16-inch depth. A 10-percent ethylene dibromide solution was applied at the rate of 22 gallons per acre and the chlorinated propane-propylene at 18, 26, and 36 gallons per acre. Each treatment and check was replicated in four randomized blocks. The materials were applied 6 to 7 inches deep, at 12-inch spacings, with the garden-tractor applicator. Soil temperatures on April 16, when the treatments were applied, ranged from 64° to 67° F. at 6 inches and from 63° to 66° at the 12-inch depth. Twelve 1/4-square-foot soil samples, to a depth of 16 inches, were taken from each plot 7 and 8 days after treatment, and wireworms found were placed individually in salve cans and examined 9 days later for mortality. Twenty additional samples of the same size were taken from each plot 10 months after treatment (Feb. 1947). Lima beans were planted on May 7 in 1946 and 1947 and on May 12 in 1948. A summary of the results appears in table 4.

From the low wireworm populations in the treated plots as compared with the untreated plots, it was evident that many of the dead larvae had not been recovered when the soil samples were sifted. However, the siftings of the soil samples taken in the bean rows showed that good control had been obtained with all dosages of both fumigants. These results are further verified by the samplings made in February. Owing to the heavy populations and the destructiveness of the wireworms, very poor yields were obtained in the check plots in 1946. In 1947, however, because of the natural reduction in wireworm populations, the yields in these plots and in the treated plots were about the same. There were no significant differences in the populations in the treated and untreated bean rows in 1948 or in the yields of beans obtained.

Field Experiments Begun in 1947

In 1947 tests were begun to determine the effectiveness of two proprietary preparations of chlorinated propane-propylene and one of ethylene dibromide against wireworms in a field of extremely sandy soil seldom producing more than 10 sacks of lima beans per acre. The plots were 1/3 acre in size, and each treatment and check was replicated three times in a randomized-block design. A commercial soil-fumigant applicator with 9 blades spaced 12 inches apart was used to apply the materials at a depth of 7 to 8 inches. A heavy plank attached to the rear of the applicator sealed any openings made by the injector blades. The moisture content of the soil at the time of treatment, on April 8, averaged 7.3, 9.1.

Table 4.-- Control of wireworms over a 3-year period with one application of soil fumigants in April 1946.
R. Borchard field.

Treatment	Rate per acre	Wireworms per square foot after treatment			Wireworms per foot of bean row			Plants per foot of bean row			Yield of dry lima beans per acre[2]		
		In samples taken after 8 days		In samples taken after 10 months[1]									
		Alive	Mortality after 9 days in salve tins		1946	1947	1948	1946	1947	1948	1946	1947	1948
	Gallons	Number	Percent	Number	Number	Number	Number	Number	Number	Number	Sacks	Sacks	Sacks
None	0	6.2	0	2.2	5.5	1	0.9	0.5	1.4	1.7	13	21	24
Chlorinated	(18	1.9	65	.5	.3	.3	1.	2.1	1.7	1.4	32	23	25
propane-	(26	2.2	93	.3	.2	.2	1.	2.1	1.7	1.6	34	22	23
propylene	(36	2.6	94	.1	.1	.1	.8	2.1	1.7	1.6	32	24	24
Ethylene dibromide solution, 10 percent by volume	22	2.7	94	.1	.01	.03	.5	2.1	1.9	1.7	33	22	26
Difference required for significance (odds 19:1)		1.6	[3]	.3	1.1	[3]	[3]	.3	.2	[4]	4	[4]	[4]

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[1] Includes adults.
[2] Total yield in 100-pound sacks.
[3] Not significant according to F test when check plots were omitted from the analysis.
[4] Not significant according to F test.

10.7, and 12 percent (by weight) at depths of 4, 8, 12, and 16 inches, respectively. Soil temperatures ranged from 56° to 68° F. at 4 inches and from 60° to 63° at 12 inches depth. Lima beans were planted in this field on May 3 in 1947 and 1948.

This field was not heavily populated with wireworms. Twenty 1/4-square-foot soil samples to a depth of 16 inches, taken in the check plots prior to treatment, showed from 0.8 to 1 wireworm per square foot.

In these tests an effort was made to ascertain the immediate effectiveness and the duration of effectiveness of the fumigants against wireworms confined in cages at different depths in the soil, and equidistant between lines of injection. Immediately after treatment and on the second and fourth days thereafter, two holes 1 inch in diameter were bored with a soil auger to a depth of 16 inches in each plot, and in each hole were inserted, one above the other, four screen cages (1 by 4 inches) each containing five medium-sized larvae of Limonius californicus. This method of cage placement made it possible to determine wireworm mortalities at depths of 0 to 4 inches, 4 to 8 inches, and 12 to 16 inches. These caged wireworms were left in the soil for 14 days. The lowest mortalities were obtained at the 0- to 4-inch depth in the plots fumigated with chlorinated propane-propylene.

As shown in table 5 all the materials gave exceptionally good mortality of wireworms in cages inserted in the soil at the time the fumigants were applied. Mortalities in cages placed in the soil after 2 and 4 days indicated that the chlorinated propane-propylene preparations decreased in effectiveness more rapidly than those containing ethylene dibromide. All treatments caused significant reductions in wireworm populations in the bean rows during the 2-year period of these tests. The soil was heavily infested with root-knot nematodes, and the increased yields of dry beans by fumigation may have been due partially to nematode control.

COMPARATIVE EFFECTIVENESS OF CHLORINATED PROPANE-PROPYLENE APPLIED AT 12- AND 15-INCH SPACINGS

During April 1946 tests were conducted in three fields to determine whether 12- or 15-inch spacings would be the most practical to use when applying chlorinated propane-propylene. The soil in these fields was Yolo fine to very fine sandy loam, with a moisture content averaging 12.4, 13.8, 13.9, and 15.6 percent (by weight) at depths of 4, 8, 12, and 16 inches. Soil temperatures ranged from 58° to 65° F. at the 6-inch depth and from 56° to 64° at the 12-inch depth. The garden tractor applicator was used, and the material was applied in a continuous flow 6 to 7 inches deep, at 12- and 15-inch spacings, for a distance of 200 feet. The rate of flow was varied by using orifices of different sizes. The tank was filled with the fumigant at the beginning and drained at the end of each test. The material was carefully measured to determine the amount used. Immediately after treatment caged wireworms were placed into the soil, as in the preceding experiment, for use in obtaining mortality records.

Table 5.—Control of wireworms over a 2-year period with one application of soil fumigants in April 1947.

Treatment	Rate per acre	Mortality after 14 days of caged wireworms placed in the soil			Wireworms per foot of bean row		Plants per foot of bean row		Yield of dry lima beans per 0.01 acre	
		Immediately after application	2 days after application	4 days after application	1947	1948	1947	1948	1947	1948
	Gallons	Percent	Percent	Percent	Number	Number	Number	Number	Pounds	Pounds
None	0	1	3	3	1.03	0.5	1	1.4	8	7
Chlorinated propane-propylene:										
Preparation 1	22	88	80	53	.18	.04	1.4	1.7	16	10
Same plus 1/2 gal. of ethylene dibromide	24	91	92	87	.13	.04	1.5	1.7	14	7
Preparation 2	24	92	86	74	.16	.04	1.4	1.8	16	10
Ethylene dibromide solution, 10 percent (by volume)	21	99	74	92	.02	.07	1.4	1.6	11	9
Difference required for significance (odds 19:1):	—	—	—	--	.2	.2	.2	1/	3	1/

1/ Not significant according to F test.

In view of the excessively moist condition of the soil at this time of the year, exceptionally good kills of wireworms to a depth of 12 inches were obtained with all dosages applied at 12-inch spacings as shown in table 6. The heaviest dosages applied at 15-inch spacings were also highly effective but were generally less effective at the lowest depth.

Table 6.--Mortality of wireworms caged for 2 weeks at different depths in soil fumigated with chlorinated propane-propylene applied at different spacings. 1946.

Gallons per acre	Total wireworms in cages	0 to 4 inches	4 to 8 inches	8 to 12 inches	12 to 16 inches	Average at all depths
	Number	Percent	Percent	Percent	Percent	Percent
			Fumigant applied at 12-inch spacings			
20	1,000	100	98	84	54	84
27	1,196	100	100	89	51	85
36	900	100	100	100	92	98
41	100	100	100	100	100	100
			Fumigant applied at 15-inch spacings			
21	499	100	98	76	25	75
31	300	100	100	100	65	91
38	100	100	100	100	100	100

EFFECTIVENESS OF CHLORINATED PROPANE-PROPYLENE IN LOOSE AND COMPACT SOILS

Some sugar-beet growers make a practice of treating their soil for wireworms and nematodes in December or January, before they plant. At this time soil temperatures average about 10° F. lower than in the spring, and the soil is considerably wetter. In December 1946, while large-scale treating of fields was in progress, tests were conducted in two fields to determine the effectiveness of these winter treatments against wireworms.

One of the fields had been plowed to a depth of 14 inches and the soil was loose, whereas the other field had not been disturbed by cultivation. On both fields the soil was Yolo sandy loam. The moisture content of the loose soil at depths of 4, 8, 12, and 16 inches averaged 12.8, 14.9, 15, and 18.6 percent (by weight) and that of the compact soil 14.5, 12.9, 13.5, and 13.6 percent. On the day of treatment, soil temperatures reached 62°, 58°, and 59° F. in the compact soil and 60°, 55°, and 54° in the loose soil at depths of 4, 8, and 12 inches, respectively. The chlorinated propane-propylene was applied to a depth of 7 inches, at 12-inch spacings, at the rate of 32 gallons per acre in the loose soil and 26 gallons per acre in the compact soil. Immediately after treatment four screen cages (1 by 4 inches), each containing five wireworms and wheat, were inserted one above the other in holes 16 inches deep bored at 12-foot intervals and equidistant between the lines of injection of the chemical. The cages were left in the soil 12 days. Forty cages were used in each field. In the loose soil all the wireworms were killed at all depths in both fields as compared with 5 to 10 percent mortalities in the cages placed in untreated soil. In the compact soil, between spacings, the mortality ranged from 100 percent at 0 to 4 inches to 80 percent at 4 to 8 and 8 to 12 inches and 56 percent at 12 to 16 inches. In the cages placed along the line of injection, the mortality ranged from 100 percent at 0 to 8 inches to 96 percent at 8 to 12 inches and 72 percent at 12 to 16 inches. All the wireworms confined in cages in the untreated soil were active. On the basis of these results, it appears that plowing or disking deeply prior to soil fumigation will insure deeper penetration of the fumes and greatly increase the effectiveness of the treatment. A plow sole between 8 and 12 inches would greatly hinder the movement of the gas to the lower depths.

EFFECTIVENESS OF FUMIGANTS APPLIED IN DRY SOILS

Most of the tests with soil fumigants were conducted in the spring, when the soil was moist and ready for seeding. In the test area many growers plant beans for 2 or 3 years in the spring and in the fall plant sugar-beets or vegetable crops, which are usually highly susceptible to wireworm and nematode attack. If a soil fumigant is used, it must be applied after harvest of the bean crop, when the soil is generally dry.

To obtain information on the effectiveness of fall treatments against wireworms, various dosages of chlorinated propane-propylene and ethylene dibromide were applied with the garden tractor applicator in October in recently plowed, dry, sandy loam soil. These chemicals were injected 5 to 6 inches deep, at 12-inch spacings for a distance of 100 feet, in soil of moisture content averaging 6 percent (by weight) between the 0- and 16-inch depths. Soil temperatures in the first 12 inches ranged from 50° to 60° F. As in the previous tests, immediately after treatment cages containing wireworms were inserted one above the other in holes bored at 15-foot intervals equidistant between lines of injection of the chemicals. The 10-percent ethylene dibromide solution was applied in quantities to obtain 1.5, 1.9, and 2.4 gallons of actual ethylene dibromide per acre. The chlorinated propane-propylene was applied at the rates of 22, 35, and 41 gallons per acre. Ten days later the cages were removed and the wireworm mortalities determined.

Both materials were highly effective, as all dosages gave 100-percent kill of wireworms at all depths. Fall applications of soil fumigants, therefore, would be highly effective, provided the wireworms were in the upper 12 inches of soil at the time of treating.

DISCUSSION

Chlorinated propane-propylene is extremely phytocidal and soil treated with this material should be thoroughly aerated 10 to 14 days after treatment. Most crops can be planted 3 to 4 weeks after treatment if the soil has been aerated properly. Ethylene dibromide is less phytocidal, and although crops such as lima beans have been planted immediately after the soil has been treated, it would be safer to withhold planting of either seed or sets of most crops for at least 10 to 14 days. Tomato transplants especially are often injured if transplanted too soon after treatment of the soil.

All tests reported on herein were conducted in fields free of clods and plant debris. The efficiency of these fumigants would no doubt be greatly decreased if partially decayed crops, such as sugar-beets, potatoes, alfalfa, or the remains of a cover crop, were present in the soil to attract wireworms.

PRECAUTIONS IN HANDLING

Chlorinated propane-propylene and ethylene dibromide are both poisonous to man and animals. The following precautions should be taken when these fumigants are being handled:

The materials should not be allowed to come in contact with the skin. If the liquid is spilled on the skin, wash it off immediately with soap and water. If it is spilled on clothing or shoes, they should be removed immediately and thoroughly cleaned before being worn again.

The fumes should not be inhaled, and care should be taken to avoid getting the liquids into the eyes or mouth.

These materials are also inflammable and they should be kept in tightly closed containers away from open fires.

SUMMARY

Experiments conducted in southern California over a period of 5 years in different soils show that the soil fumigants chlorinated propane-propylene and ethylene dibromide, when applied 7 to 8 inches deep, at 12-inch spacings, gave exceptionally good control of the sugar-beet wireworm (*Limonius californicus* Mann.) for 2 years.

Ethylene dibromide was found to be highly effective when applied at a dosage of 2 gallons, or 36 pounds, of technically pure material per acre. Commercial preparations containing 10 and 20 percent of ethylene dibromide (by volume) in a petroleum naphtha thinner were effective at 20 and 10 gallons per acre, respectively. In extremely heavy soils these dosages are not always effective against wireworms 12 to 16 inches deep.

Chlorinated propane-propylene has given exceptionally good control of wireworms to a depth of 12 inches when applied at dosages between 26 and 36 gallons per acre and yields of lima beans were greatly increased, due perhaps in part to its value as a nematocide.

Dragging a heavy chain or steel bar behind the applicator served to seal the openings in the soil made by the injector blades and helped to compact the soil and thereby retard escape of the gas.

These materials were also less effective when applied in hard, compact soils that had not been disturbed by cultivation. The best results were obtained when the soil had been plowed or disked deeply.

Extremes of soil temperature or moisture at the time of treatment did not appear to lessen the effectiveness of these materials. The treatments were applied from the third week in March to the last week in May, when soil temperatures ranged from 56° to 78° F. at the 4-inch depth and from 60° to 68° at the 12-inch depth, and the moisture content (dry-weight basis) from 6 to 14 percent and 15 to 18 percent at the respective depths. It would not be advisable to treat soil too wet to work or soil that has formed a crust following a rain.

Because of the receding soil moisture and general movement of the wireworms to lower depths, such as occurs in bean fields, fall applications of soil fumigants to control wireworms are not practicable. Nevertheless, as judged by the high mortalities of wireworms in cages, fall applications were highly effective when made on dry, loose soils containing only 6 percent of moisture in the first 12 inches and when soil temperatures in this area ranged from 50° to 60° F.

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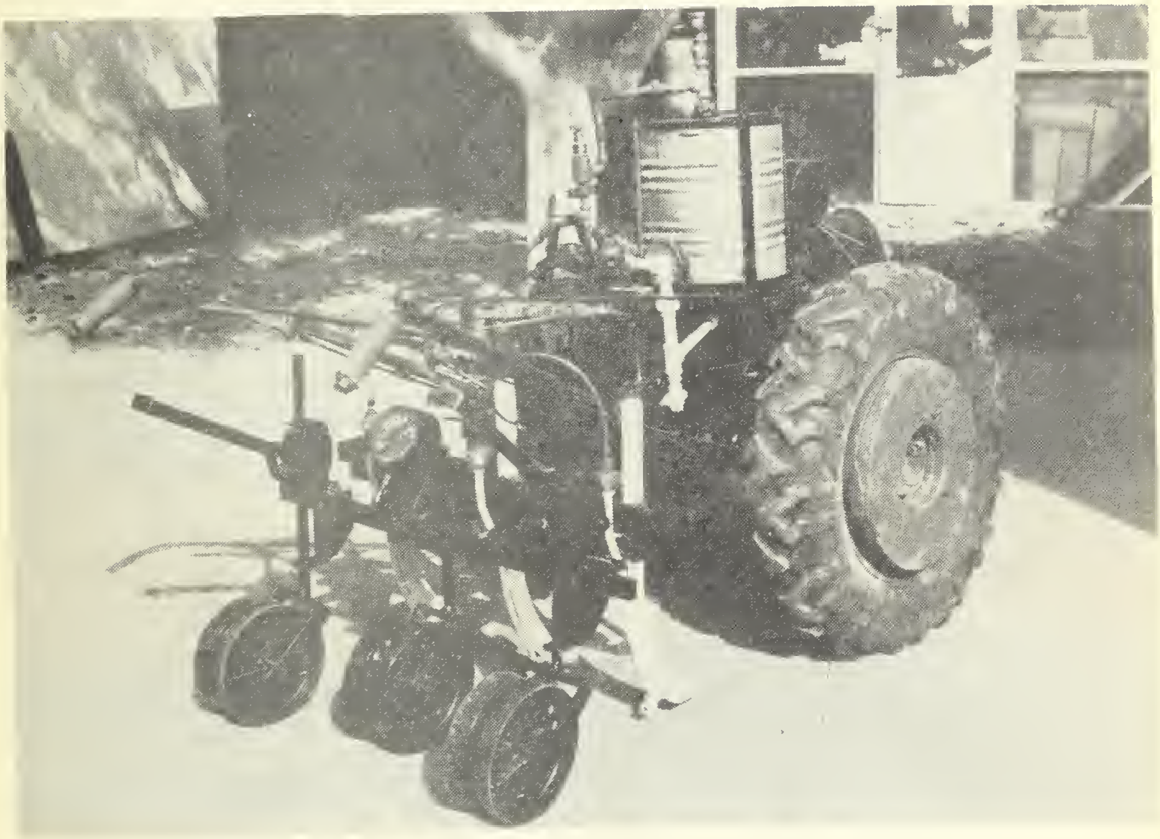

Figure 1.--Garden tractor applicator for applying soil fumigants in field plots.

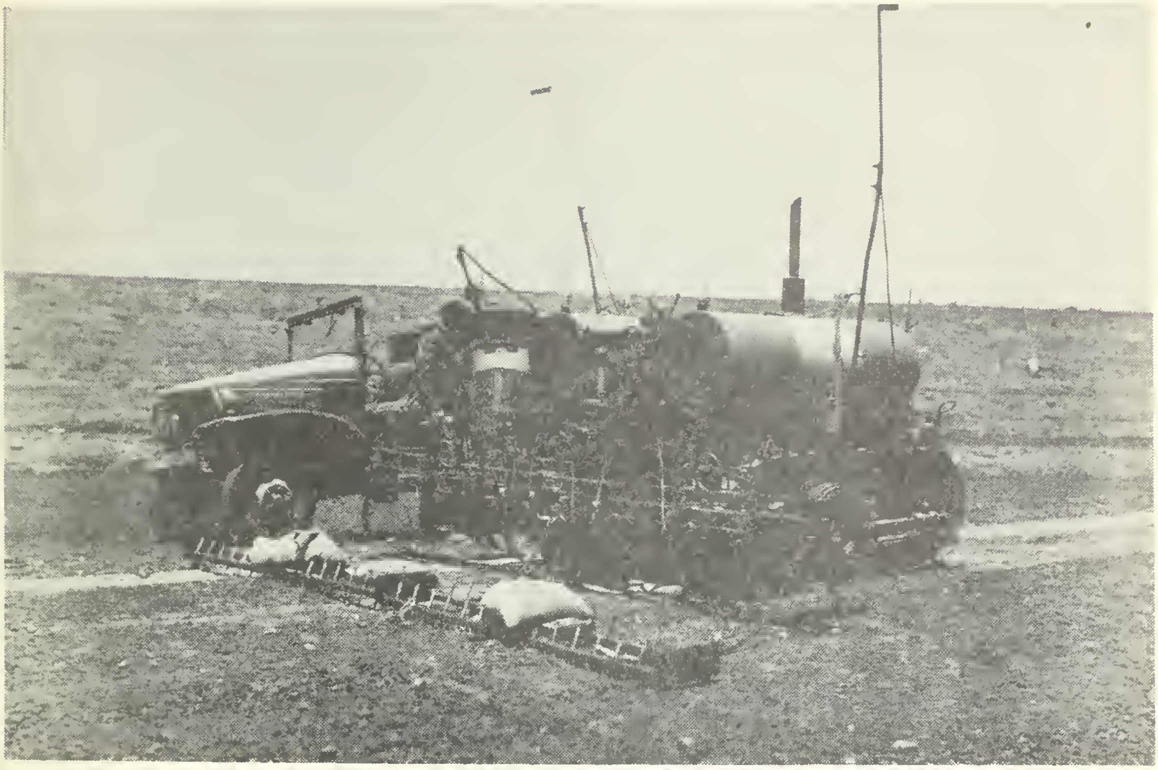

Figure 2.--Tractor-propelled 11-blade applicator used in treating large wireworm-infested fields with soil fumigants.

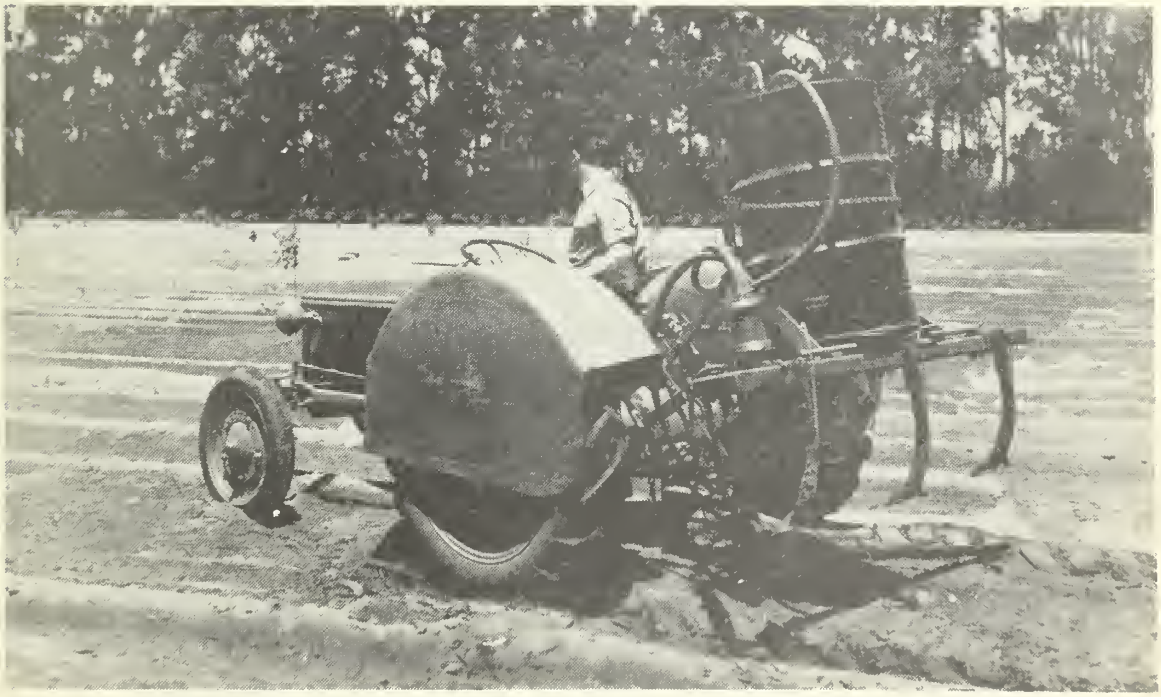

Figure 3.--Soil-fumigant apparatus mounted on wheel-type tractor used for treating small areas infested with wireworms.

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